NEUTRON STAR DYNAMICS, BRAKING INDICES AND ENERGY DISSIPATION

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Abstract

Models of pulsar glitches and postglich relaxation are reviewed. Implications for braking indices due to internal torques in the neutron star, and energy dissipation by internal torques are discussed. All recent observations of pulsars with large (Vela pulsar like) glitches and second derivatives are seen to fit with the same glitch dynamics that the Vela pulsar exhibits.

1. Introduction

Pulsar glitches and postglitch relaxation constitute our main source of information on the structure and dynamics of neutron stars. With more young pulsars discovered and monitored in recent surveys at Jodrell Bank and Parkes, the growing glitch sample includes some 44 glitches from 21 pulsars (Shemar and Lyne 1996). The fractional change $\Delta\Omega/\Omega$ in the pulsar rotation frequency has a wide range, varying from 10^{-9} to a few times 10^{-6}. The Crab pulsar exhibits small ($\Delta\Omega/\Omega \sim 10^{-8}$) glitches, some of the individual pulsars with repeated glitches have glitches with $\Delta\Omega/\Omega \sim 10^{-7} - 10^{-6}$ only, while several (the Vela pulsar, PSR 1737-30 and PSR 1758-23) have both small and large glitches, but with a gap of at least a factor 3.5 in $\Delta\Omega/\Omega$ between their small and large glitches. No individual pulsar has a continuous distribution of all glitch sizes. The glitch size distribution seems to be bimodal. The Vela pulsar, which has been the most regular and well studied source of glitches over the last twenty seven years, has exhibited eleven large ($\Delta\Omega/\Omega \geq 10^{-6}$) glitches at almost regular intervals of about two years, with three occasional small glitches. The glitch activity parameter applied by Lyne (1996) to the statistics of glitches indicates that glitch rates scale with $|\dot{\Omega}|$. The statistics of large glitches from all pulsars is consistent with the hypothesis that these events occur at intervals $t_g = \delta\Omega/|\dot{\Omega}|$ (Alpar and

Baykal 1994). It should be noted that this $\delta\Omega$ is *not* the observed increase $\Delta\Omega$ of the rotation rate of the neutron star's crust. In vortex unpinning models $\delta\Omega$ is the sudden loss of rotation frequency in the pinned superfluid due to vortex motion at a glitch. $\delta\Omega$ is related to the observed spin-up $\Delta\Omega$ of the crust by angular momentum conservation, so that in a glitch the angular momentum lost by the pinned superfluid is transferred to the crust. This angular momentum balance is expressed in Eq.(5) below. The value of $\delta\Omega$ as inferred from fits to the Vela pulsar's glitches (or, possibly better still, the value of $\delta\Omega/\Omega$) also provide agreement with the glitch statistics from all pulsars older than the Vela pulsar. Thus the large glitches with $\Delta\Omega/\Omega > 10^{-7}$ seem to be occurring at rates proportional to $|\dot{\Omega}|$ in all older pulsars. For a number of reasons it is impossible to explain the large glitches of the Vela pulsar, occurring at the observed rate of roughly once every two years, in terms of starquakes. The basic problem for starquake models for the Vela glitches, noted first by R. Epstein, is that the observed magnitude and rate of glitches imply a rate of shape relaxation for the solid component that is about two orders of magnitude larger than the relaxation rate that a fluid star would have.

In the Vela pulsar the glitch parameters, postglitch behaviour and intervals between glitches can all be understood in terms of a model of angular momentum exchange between the superfluid in the inner crust of the neutron star where vortices are pinned and the rest of the star. In the Crab pulsar, a similar picture of angular momentum exchange is successfully applied to explain the glitches in rotation frequency along with the accompanying "persistent shifts" in the spindown rate. While breaking of the neutron star's solid crust ("crustquakes") is not ruled out for the Crab glitches, whose magnitudes $\Delta\Omega/\Omega \sim 10^{-9}$ is about three orders smaller than that of the Vela glitches, crustquakes cannot explain the persistent shifts. Vortex unpinning alone is also insufficient as it cannot explain the occurrence rate of the glitches. Quakes and vortex unpinning are invoked in conjunction in various models for the Crab pulsar glitches (Alpar et al 1996, Ruderman 1993).

Comparison of the models developed for the Crab and the Vela glitches, along with the statistics of glitches from the entire pulsar sample has led to the conjecture that the glitch behaviour of a pulsar evolves from "Crab-like", with small glitches alone, to "Vela-like", with predominantly large glitches with the occasional small glitch (Alpar et al 1996, Alpar 1995, Alpar and Pines 1993, Alpar et al 1993). These papers contain references to earlier work introducing the basic concepts. The next section reviews the basic features of glitches and postglitch behaviour within this evolutionary framework. In Section 3 , we discuss the consequences for observations of the pulsar braking index, and compare with observations, while Section 4 discusses the rates of energy dissipation expected to accompany the angular momentum exchange inside the neutron star at glitches and due to vortex creep during the interglitch epochs.

2. Postglitch Behaviour and Nonlinear Dynamics

Let us summarize the main features of glitch models without going into the details of the application to the Crab and Vela pulsars' glitches. As in any rotating multicomponent system with external torques acting on the "outer" component, the rotation frequency Ω_s of an interior component of the neutron star follows the spindown of the crust at some lag in rotation frequency, so that $\Omega_s > \Omega_c$, the rotation frequency of the crust. The internal torque between the interior component and the crust achieves the angular momentum transfer from the interior to the crust. As the interior spins down, there is a corresponding spin-up torque from the interior on the crust. The crust spins down under the combined effect of the external spindown torque from the pulsar magnetosphere and the spinup torques from the interior. The internal torque coupling an interior component with the crust is a function of the lag $\omega = \Omega_s - \Omega_c$ which depends on the physical coupling mechanism. In normal stars this mechanism is viscosity. A steady state is reached at a lag ω at which the interior and the crust spin down at the same rate.

In the superfluid interior of the neutron star, angular momentum transfer to the crust can take place only through the (radially outward) motion of the quantized vortex lines. The spindown rates of the superfluid components and the resulting contributions of internal torques to the observed spindown rate of the pulsar are proportional to the vortex current. The mechanism that sets up a vortex current in response to the lag ω is the interaction between the vortex lines and ambient normal matter, like the electron gas or the crystal lattice in the inner crust. The resulting vortex current and spindown rate can be linear in ω, as in ordinary viscous coupling, or can have a very sensitive nonlinear dependence on ω, as for thermally activated vortex creep or quantum tunnelling against pinning forces that tend to pin vortex lines on local inhomogeneities like nuclei in the inner crust lattice. The extreme form of nonlinear response of the vortex current is when vortices are pinned within a "vortex trap" region until ω reaches a critical value beyond which the local pinning forces can no longer sustain the pinning, and a sudden discharge of the pinned vortices ensues, the resulting angular momentum transfer to the crust being observed as a glitch.

We can think of the dynamics of the pinned superfluid in terms of a "network" carrying the vortex current (Alpar 1995). The vortex traps are the "capacitors" which can transfer angular momentum only at vortex discharges. The resulting sudden spinups of the crust are the observed glitches. Between glitches, the traps do not contribute to the spindown of the superfluid. Therefore there is no contribution from these regions to the change in spindown rate of the crust that accompanies a glitch. If such a vortex trap is formed as part of the glitch event, then there will be a permanent change in the spindown rate (a "persistent shift", as observed in the Crab pulsar glitches), since the newly formed trap region sustained vortex currents before the glitch and can no longer do so after the glitch.

Other parts of the pinned superfluid will sustain a continuous vortex current. These are analogous to resistors in an electronic circuit. There will be a continuous contribution to the spindown of the superfluid, and the corresponding continuous internal spinup torque acting on the crust. In response to the changes in ω associated with the glitch, the vortex currents undergo changes that then relax back. These are reflected as postglitch response in the observed spindown rate of the crust. For internal torques that are linear in the lag ω, the response to glitch induced perturbations takes the form of simple transients that relax exponentially with time. Such transients are observed after the Crab and Vela pulsar glitches. When the transients are over, a much slower response takes over. In the Vela pulsar this response takes the form of an approximately constant positive second derivative of the rotation frequency which relates to the glitch parameters and is much larger than the second derivative from the pulsar braking law with braking index n=3. This kind of postglitch response is easily understood as the response of the vortex current if its dependence on the lag ω is very nonlinear, as it can be for thermally activated vortex creep. To avoid confusion in terminology, one needs to note that linear dependence of the vortex current on the lag gives exponential relaxation, while nonlinear dependence means a slow response in which the postglitch spindown rate may suffer a stepwise decrease, and recover gradually as only a linear function of time. The increase in the crust rotation rate and the decrease in the superfluid rotation rate at a glitch offset the lag ω from its steady state value required for spindown of the superfluid at the steady state rate. The vortex current can then practically stop in a region where vortex creep is in the nonlinear regime. This decouples that region from the effect of the external torque. As the external torque now acts on less moment of inertia, the spindown rate of the neutron star increases. This state of affairs will last for a "waiting time" $t = \delta\omega/|\dot{\Omega}|$ after which the spindown of the crust has built the lag back to its initial value and vortex creep starts again. The signature of this nonlinear behaviour would be a stepwise decrease in the spindown rate at the time of the glitch, and a stepwise increase after the waiting time, if all parts of the nonlinear creep regions had suffered the same offset $\delta\omega$ at the glitch. However, the lowest moment of the glitch induced vortex unpinning is the unpinning of a uniform density of vortices. This corresponds to a linear dependence of $\delta\omega$ on radius, and translates to a range of waiting times, so that the collective effect of nonlinear creep response is an initial offset in spindown rate that recovers linearly in time, as can be shown easily.

The difference between the glitch signatures of the Crab and Vela pulsars and the statistical evidence that all pulsars older than the Vela pulsar have a similar glitch signature to that of Vela, with glitch rates scaling as expected with the spindown rate has led to an evolutionary picture of glitch behaviour (Alpar and Pines 1993, Alpar 1995). The Crab pulsar is in the process of establishing a network of vortex traps. A pulsar at Vela's age already has a network that saturates its pinned superfluid regions and controls a moment of inertia of a few percent of the total moment of inertia. Such a saturated network can sustain collective unpinning events in which vortex unpinning builds into an avalanche in which all traps participate. Vela and older pulsars have large glitches with the occasional small glitch for network rearrangement. The Crab pulsar has small ($\Delta\Omega/\Omega \sim 10^{-9} - 10^{-8}$) glitches which are simultaneous crust breaking and vortex unpinning events. The breaking of the crust introduces new vortex traps. The persistent shift is just the moment of inertia of these trap regions as a fraction of the star's total moment of inertia. To build up to the total moment of inertia fraction of a few percent inferred from the Vela pulsar glitches will take of order 10^2 Crab like glitches, and this initial network building phase will last some thousands of years at an average interglitch time of order 10 years. The statistics of the small glitches from old pulsars is of great interest to test this evolutionary picture, which predicts that small glitches take place only occasionally in old pulsars with a rate determined by crust breaking as a trigger.

The detection of persistent shifts in the spindown rate associated with Crab like glitches from old pulsars will also be interesting. The small glitches detected in the Vela pulsar do not give the possibility to resolve a persistent shift of order 10^{-4} because the excursions in spindown rate associated with the large glitches of the Vela pulsar are about two orders of magnitude larger. If such unresolved changes in spindown rate occur they would have a contribution to the long term braking index measurements. This effect may be responsible for the braking index of 1.4 recently reported for the Vela pulsar, as we discuss in the next section.

3. Effect of Glitches and Postglitch Response on Braking Indices

Glitch dynamics can contribute to the pulsar braking index in two simple ways: (i) the effect of unresolved persistent shifts in spindown rate, and (ii) the contribution of long term interglitch recovery which has a second derivative that relates to the glitch parameters.
The braking index n is defined through

$$\dot{\Omega} = -k\Omega^n \tag{1}$$
$$n = \Omega\ddot{\Omega}/\dot{\Omega}^2 \tag{2}$$

The coefficient k is:

$$k = 2\,M^2/(3\,Ic^3) \tag{3}$$

A braking index n=3 characterizes pure dipole braking of a pulsar whose magnetic moment M and moment of inertia I are constant. There are four young pulsars with measured braking indices, which are less than three in all cases (Lyne et al 1993, Boyd et al 1995, Kaspi et al 1994). An increase in the magnetic moment (Ruderman 1993) or a decrease in the effective moment of inertia that couples to the spindown of the crust will make the braking index less than three:

$$n = 3 - (2\dot{M}/M - \dot{I}/I)\Omega/|\dot{\Omega}| \tag{4}$$

A recent analysis of Vela pulsar timing data spanning many glitches led to a braking index n=1.4 after the postglitch response contributions were taken into account (Lyne et al 1996). The occasional small glitches, comparable in $\Delta\Omega/\Omega$ to the Crab pulsar glitches, may well have associated persistent shifts in the spindown rate that cannot be resolved against the background of the much larger changes in spindown rate associated with the postglitch response to the regular large glitches of the Vela pulsar. As discussed above, a persistent shift reflects a reduction in the effective moment of inertia coupled to the crust spindown. If an unresolved persistent shift $\Delta\dot{\Omega}/\dot{\Omega} = 3\times10^{-4}$ occurs about once every four years in the Vela pulsar, this will be enough to give a long term braking index n=1.4. In the evolutionary picture of glitch behaviour, formation of vortex traps and the frequent occurrence of events with persistent shifts is a characteristic of young pulsars. Unresolved events with persistent shifts may be responsible for the observed n<3 in young pulsars. Further, we note that the distribution of pulsars in the $P-\dot{P}$ diagram suggests that young pulsars follow tracks with n<3 until ages of the order of 10^4 years, after which they "drop" to n=3 tracks (Yusifov et al 1995). This would be expected qualitatively in the glitch evolution model if vortex trap formation saturates and becomes rare in older pulsars.

The interglich behaviour of older pulsars is characterized by a constant second derivative of the rotation frequency after the postglitch transients are over. The vortex creep theory predicts that as a pulsar cools, nonlinear response will characterize more and more moment of inertia in the pinned superfluid, replacing linear response. Exponentially relaxing transients will be replaced with the characteristic response of nonlinear creep, which is a slow recovery of the spindown rate at a constant second derivative of the rotation frequency. Even without such a transition due to cooling of the neutron star, if one argues that all relaxation and interglitch timescales are determined by neutron star physics except for their dependence on the external torque, they should scale with $|\dot{\Omega}|^{-1}$ from the set of relaxation times in the Vela pulsar. In the Vela pulsar the relaxation times of postglitch transients range from 10 hours to 32 days while the time between gltiches is of the order of two years, and throughout this interglitch interval the nonlinear response at constant second derivative continues. A typical pulsar will be glitching at intervals of several hundred years; and, scaling from the Vela pulsar, there is only a 5% chance that a random timing observation of the pulsar will fall in the epoch of transients following a glitch. Recent measurements of second derivatives corresponding to anomalously high braking indices can be evaluated as due to interglitch recovery of nonlinear creep. The agreement with the model developed for the detailed fits to the Vela pulsar's interglitch behaviour is remarkable.

The vortex creep model was applied to the long term angular momentum transfer in the Vela pulsar after the linear response, exponentially relaxing transients are over. There are three observed quantities: $\Delta\Omega$, the increase in the rotation frequency at the glitch; $\Delta\dot{\Omega}$, the increase in the spindown rate at the glitch, and $\ddot{\Omega}$, the interglitch second derivative of the rotation rate after the transients are over. The model identifies two kinds of nonlinear response regions in the pinned superfluid. I_B/I denotes the moment of inertia fraction in the vortex capacitors which allow vortex motion only in glitches and thereby undergo a decrease in superfluid rotation rate $\delta\Omega$. This component has no contribution to the continuous spindown rate or to its changes in the glitch or as a second derivative of the rotation rate. I_A/I denotes the moment of inertia fraction in the nonlinear creep regions connecting the vortex capacitors. At a glitch these regions undergo an average decrease $\delta\Omega/2$ in superfluid rotation rate. Their vortex currents and contribution to spindown is completely stopped as a consequence of the glitch, giving a fractional change in the spindown rate equal to I_A/I, which then relaxes as a linear function of time (at a constant second derivative of the rotation rate) to the lowest approximation corresponding to a uniform density of unpinned vortices in the glitch. This behaviour extends till the next glitch. The model predicts the time to the next glitch as $t_g = \delta\Omega/|\dot{\Omega}|$.

The equations relating these model parameters to the observed glitch parameters are (Alpar 1995):

$$\Delta\Omega = (I_A/2I + I_B/I)\delta\Omega \quad (5)$$
$$\Delta\dot{\Omega}/\dot{\Omega} = I_A/I \quad (6)$$
$$\ddot{\Omega} = (I_A/I)(\dot{\Omega}^2/\delta\Omega) \quad (7)$$

From these equations we can express $\ddot{\Omega}$ as

$$\ddot{\Omega} = (\beta + 1/2)((\Delta\dot{\Omega}/\dot{\Omega})^2{}_{-3}/(\Delta\Omega/\Omega)_{-6})(\dot{\Omega})^2/\Omega \quad (8)$$
$$n = (\beta + 1/2)((\Delta\dot{\Omega}/\dot{\Omega})^2{}_{-3}/(\Delta\Omega/\Omega)_{-6}) \quad (9)$$

where $\beta = I_B/I_A$ and glitch parameters are scaled to characteristic values, e.g. the fractional change in rotation rate is $10^{-6}(\Delta\Omega/\Omega)_{-6}$. The time to the next glitch can be expressed as

$$t_g = \delta\Omega/|\dot{\Omega}| = 2 \times 10^{-3}(\beta + 1/2)\tau\,((\Delta\Omega/\Omega)_{-6}/(\Delta\dot{\Omega}/\dot{\Omega})_{-3}) \quad (10)$$

where $\tau = \Omega/2|\dot{\Omega}|$ is the pulsar's spindown age. Table 1 lists all glitches with $\Delta\Omega/\Omega > 10^{-7}$ with subsequent $\ddot{\Omega}$ measurements reported by Lyne and Shemar(1996). The observed value of $\ddot{\Omega}$ and the corresponding value of the braking index are listed together with the glitch parameters $\Delta\Omega/\Omega$ and $\Delta\dot{\Omega}/\dot{\Omega}$ and the value of β implied if the $\ddot{\Omega}$ is indeed due to interglitch recovery. We find that β is between 0.4 and 6 for all cases. This lends strong support to the idea that Vela-like glitch behaviour is indeed common to all pulsars older than Vela. This was first proposed for the Geminga pulsar to explain $\ddot{\Omega}$ assuming Geminga has Vela like glitches (Alpar, Ögelman and Shaham 1993). The limited variation in β may indicate that the ratio of capacitive to resistive parts of the vortex current network may vary between neutron stars, reflecting differences in the build-up history of the vortex trap network. Part of the variation may also be due to contamination by transients in the older pulsars.

PSR 1737-30, which has an age and glitch activity comparable to the Vela pulsar's, has been observed to glitch repeatedly. If we apply the model to the large glitches, with $\Delta\Omega/\Omega > 10^{-7}$, we can use the β values obtained from the observed $\ddot{\Omega}$ to estimate the time between two consecutive glitches. These estimates are compared with the observed interglitch intervals, showing an encouraging agreement to 20% for the two pairs of consecutive large glitches for which data are available.

TABLE 1.

Glitch	$(\Delta\Omega/\Omega)_{-6}$	$(\Delta\dot{\Omega}/\dot{\Omega})_{-3}$	$\ddot{\Omega}$	β	n	t_g
1727-33	3.07(1)	9.7(7)	628	0.74	38	253 yrs
47990(20)						
1737-30	0.427(10)	4.1(4)	1098	4.1	181	341 d
46991(40)						290±44 d
1737-30	0.6019(5)	2.3(2)	346	6.	57	604 d
47670(4)						516±10d
1800-21	4.073(16)	9.1(2)	867	0.4	18	17 yrs
48245(20)						
1823-13	2.718(26)	6.8(1)	1200	1.5	34	18 yrs
46507(60)						
Geminga	1.*	5.*	1-3	0.5	10-30	100-300 yrs

Glitches with $\Delta\Omega/\Omega > 10^{-7}$ and measured postglitch $\ddot{\Omega}$ values in units of 10^{-24} rad s^{-3}. The first column lists the pulsar names and glitch dates in MJD. Glitch parameters are taken from Shemar and Lyne(1996). n is the braking index. The model parameter β is given by Eq.(8). t_g is the time to the next glitch estimated with Eq.(10). For PSR B1737-30, the observed time intervals to the next glitch are also listed with errors due to the uncertainties in glitch dates. The last row applies the model to Geminga with assumed glitch parameters marked with asterisks.

4. Energy Dissipation in Glitches and Vortex Creep: Making Old Neutron Stars Observable?

The energy dissipation accompanying the angular momentum transfer in a glitch is

$$\Delta E_{diss} = \omega \Delta J = (I_A/2I + I_B/I)\omega\delta\Omega \tag{11}$$

where ΔJ is the angular momentum transfer across the preglitch lag ω between the pinned superfluid and the crust. This energy is dissipated in the inner crust, at densities $\sim 10^{14}$ gm cm^{-3} where the pinned superfluid is located. A thermal luminosity

$$\Delta L = \Delta E_{diss}/\tau_{th} \tag{12}$$

will emerge from the neutron star surface on the timescale τ_{th}, the thermal conduction time from the inner crust to the surface. With the Vela pulsar's glitch parameters, $\Delta E_{diss} \sim 10^{39}$ ergs , and with estimates of $\tau_{th} \sim 10^6$ s (Van Riper et al 1991) results of recent target of opportunity observations with ROSAT and XTE to look for excess thermal x-rays following the 11th glitch of the Vela pulsar will be of great interest.

The continuous rate of energy dissipation in vortex creep is:

$$\dot{E}_{diss} = I_A \omega |\dot{\Omega}| \tag{13}$$

Note that this is significant only for nonlinear coupling between components of the star: in that case $\omega > \delta\Omega \sim 10^{-2}$ as determined from the Vela pulsar glitches, such that $\dot{E}_{diss} \sim 10^{31}$ ergs s^{-1} in the Vela pulsar, while linear coupling would give $\omega = |\dot{\Omega}|\tau$ and $\dot{E}_{diss} = I_A(|\dot{\Omega}|)^2\tau \sim 10^{30}$ ergs s^{-1} even for a relaxation time $\tau = 1$ yr in the Vela pulsar and would be much smaller in older pulsars. The contribution of $\dot{E}_{diss}$ to the X-ray luminosity is small compared to the cooling luminosity in young neutron stars, and somewhat smaller but comparable to the observed thermal luminosity (Ögelman 1995) in the Vela pulsar. For older pulsars $\dot{E}_{diss}$ will determine the neutron star's surface temperature (Alpar, Nandkumar and Pines 1985, Shibazaki and Lamb 1989, Ögelman 1995). This has an important implication as a possible detection channel for the galactic population of "old" neutron stars. There is no evidence for decay of the dipole magnetic field in the population of observed ordinary (ie not millisecond) pulsars (eg Bhattacharya et al 1992, Hartman et al 1996). If the pulsar activity turns off as a result of spindown alone, the neutron star is still experiencing the dipole radiation torque, and there will be energy dissipation due to the lag in rotation rate between the crust and the pinned superfluid. Noting that $\omega > \delta\Omega$, from Eqns (5) and (13) we find

$$\dot{E}_{diss} > (\Delta\Omega/\Omega)\, \dot{E}_{rot}/(\beta + 1/2) \sim 10^{-6}\dot{E}_{rot} \tag{14}$$

for the energy dissipation rate by vortex creep in an old neutron star which has similar dynamics, and occasional large glitches as pulsars. Here $\dot{E}_{rot} = I\Omega|\dot{\Omega}|$ denotes the rotational energy loss rate of the neutron star. Using approximate expressions $\Omega \cong 6\, {t_6}^{-1/2}$rad s^{-1} and $\dot{\Omega}_{-13} \cong -{t_6}^{-3/2}$rad s^{-2} for a neutron star of moment of inertia $I = 10^{45}$ gm cm^2 and radius 10^6cm at age $t_6 \times 10^6$yrs subject to spindown by dipole radiation with a magnetic field $B = 10^{12}G$ we find the thermal luminosity $\dot{E}_{diss}$ and surface temperature T_s

$$\dot{E}_{rot} \cong 6 \times 10^{32} {t_6}^{-2} \mathrm{ergs\, s^{-1}} \tag{15}$$

$$\dot{E}_{diss} > 6 \times 10^{26} {t_6}^{-2} \mathrm{ergs\, s^{-1}} \tag{16}$$

$$T_s = (\dot{E}_{diss}/4\pi R^2\sigma)^{1/4} > 3 \times 10^4 K\; {t_6}^{-1/2}. \tag{17}$$

There may be 10^5 neutron stars of age 10^7 years, luminosity $> 6 \times 10^{24}$ ergs s^{-1} and $T_s > 10^4 K$, and 10^6 neutron stars of age 10^8 years, luminosity $> 6 \times 10^{22}$ ergs s^{-1} and $T_s > 3 \times 10^3 K$. This prospect of abundant but dim thermal point sources in the uv, optical and infrared bands presents a very interesting but difficult observational challenge.

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